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A RULE-BASED SYSTEM
FOR SHIPBOARD AIR DEFENSE

by

Ming-Hua Wang

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Thesis Advisor: Yuh-jeng Lee

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A Rule-Based System

for Shipboard Air Defense

by

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Submitted in partial fulfillment of the requirements
for the degree of

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ABSTRACT

This thesis examines the practicality of using an expert system approach in designing an intelligent air defense system to assist the Officer in Tactical Command (OTC) onboard a ship to make efficient and accurate decisions in critical situations in the battlefield. We analyzed modern anti-ship weapons and the counterattack measures. We also formalized some of the decision making processes and designed a computer simulation system. The system receives preprocessed sensor input, determines what contacts are present, performs target analysis and correlation based on current tactical situation, and suggests the best possible actions to take. The simulation results showed that the system can be used to speed decision making and response time in a time-critical combat environment.

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I INTRODUCTION

A. GENERAL

Today's navies are facing an unprecedented challenge in modern warfare. Since the Second World War, the task of protecting a naval force from aerial attack has been recognized as an enormous undertaking. In earlier days, a critical condition for a battle ship's survival lay in its ability to implement and execute complicated procedures for defending against a myriad of torpedoes and dive bombers escorted by fighters.

At present, sophisticated attack aircrafts will not appear in large numbers as they did before. But what makes them vastly different from the aircraft of the past is the quantum leap in all aspects from performance to firepower. Gone are those rudimentary iron bombs and torpedoes which were used to cripple naval vessels. Instead, they have been replaced by "smart weapons" carrying the most destructive warheads ever.

The necessity for aircraft to maneuver to bring their weapons to bear on a target is a thing of the past as more effective weapons can now be released at stand-off ranges. More importantly, modern anti-ship weapons can cruise at slightly above wave height and at transonic speeds, making early detection difficult, if not impossible. This translates into a sharp reduction of time allowed for a ship to organize the appropriate countermeasures. The time for reaction will be further reduced as future weapons become available that can maneuver at supersonic speed.

Expert systems have been successfully constructed for applications to a wide range of problems such as medical diagnosis, industrial process control, and air traffic control. It is desirable that one be constructed to advise the Officer in Tactical Commend (OTC) in critical operations in a tactical environment. In a highly dynamic tactical environment, major decisions have to be made by one naval officer, the OTC, who is required to respond to a vast amount of diverse information, received from a multitude of sensors, in an extremely time critical and high pressure situation. In addition to the OTC's experience, an expert system with combat direction capabilities would be a valuable tool to help the OTC respond in a timely manner, to a wide variety of adverse situations. In this thesis, we report the design and implementation of a system that is aimed at providing support to the tactical commander of a ship in air defense warfare.

B. PROBLEM

The reasons for using an expert system to aid decision making in tactical air defense warfare are as follows:

- The increased speeu of weapons systems has reduced the time available for making tactical decisions by human decision makers. This requires greater capabilities to meet the incoming threats and can be partially automated through the use of computers.
- Weapons technology has progressed to the point that no single human decision maker can be proficient in all offensive and defensive options; even if such an expert exists, there will not be enough time for him to absorb all information and execute all decisions without any error.
- In the area of military tactical operations, knowledge and data are closely related in the decision making process.
- A tactical situation is usually presented to the OTC with a view of the "state of the world". This view can be inaccurate. Nonetheless, based on this incomplete information he must make decisions subject to the constraints imposed by preplanned actions.

C. APPROACH

The above discussion illustrates the need for using an intelligent expert system to help the decision making process. This process consists of three phases: acquisition, analysis and decision. In the acquisition phase, the expert system receives data from various sensors, intelligence resources, or human interfaces, and storing that information in its dynamic database. In the analysis phase, the expert system scans its database for possible information, performs necessary calculations to verify correlation, and updates its database as appropriate. In the decision phase, the expert system indicates actions to take in a given situation based on current directives which should be followed, or based on similar situation which are familiar.

The remaining of the thesis is organized as follows: Chapter II analyzes the characteristics of anti-ship weapons, Chapter III discusses the ship's countermeasure tactics, Chapter IV defines an expert system structure and Chapter V presents the system knowledge-rule base and for system simulations, Chapter VI summarizes the work and suggests possible areas for further research.

II. MODERN ANTI-SHIP WEAPONS

A. THE DEVELOPMENT OF ANTI-SHIP MISSILES

Anti-ship missiles (ASMs) are becoming one of the most effective weapons in modern sea warfare. In the well-publicized instances when they were used against contemporary naval vessels they were successful in penetrating the defense and created severe damages. The first victim was the Israeli destroyer Eilat which was sunk in 1967 during a naval encounter with the Egyptian Navy; the second was the Royal Navy destroyer Sheffield during the Falkland Conflict; and the latest was the USN frigate Stark in the Persian Gulf.

In the late '50s the Soviet-built Styx ASM was the first weapon of this kind. Its first use in combat came as a total surprise and resulted in the sinking of the Eilat. After 30 years this weapon is still in service but it has undergone numerous technical improvements since its inception. Warheads, homing sensors and guidance systems have been modernized and the range next to trajectory performance have been enhanced. While the Styx has been retired from the Soviet Navy it continues to exist in communist China under the name "Silkworm". It has been in service with their Navy and in coastal defense. In the Iranian Forces Silkworm ASMs are showing their effectiveness in the battle for the oil resources and shipping routes in the Persian Gulf. In the '50s and '60s the Western countries had no comparable armament for their vessels and several crash programmes were initiated for closing this gap. By the early '70s several Western ASM designs finally made their appearance with operational units. The first was Israeli Aircraft Industries' Gabriel, closely succeeded by the French

Aerospatiale's Exocet. This was followed in the USA by the McDonnell Douglas Harpoon. Also, the Italian firm OTO Melara and the French company Matra together placed the ASM Otomat on the market. These weapons outperform Styx in every aspect. But the Soviet did not remain idle and fielded a wide range of new high performance ASMs.

Indeed, the current missile threat to naval ships is already formidable and appears be growing more serious in the future. At the present the most advanced ASMs feature a range between 15 and 300 km and can carry an explosive charge of up to 300kg with a speed of close to 1,000km/h. Depending on the intended target the warhead can contain simply a high explosive charge or armor-piercing shaped charges with self-adjusting fuzes which can penetrate virtually the thickest steel on ships. Even for a heavily armored ship an ASM can, therefore, cause severe damages and easily destroy or at least distort the armored flighted of an attack carrier, thereby effectively terminating fixed-wing air operations for a considerable length of time. The terminal attack trajectory of an ASM can also be adjusted to achieve maximum damage to its target and to make defense against it more difficult. For example, the missile can be programmed to climb to an altitude close to the target and dive into it vertically from above.

Compared to other weapon systems ASMs are relatively light-weighted. Together with compactness of the fire control equipment, it is practical to have them installed on combat vessels as small as fast patrol boats and facilitates for coastal defense tasks in the form of mobile batteries. Essentially ASMs can be launched from any suitable platform. It may be a small or a large vessel, an aircraft or a submarine. ASMs can therefore be regarded as ideal weapons for naval warfare of today and the future. The combat potential of existing missiles

is constantly being improved. The latest models are equipped with "smart" sensors which permit firing the weapons into the general direction of suspected enemy forces without aiming it at a previously selected target. Prior to launching the weapon's computer and sensors are programmed to search for and identify a specific type of target. As soon as the ASM is within radar or visual range of the opponent, the inboard computer is presented with a selection of digitalises electronic images of the target. It rapidly compares the presented image with those stored in its library and if one of these matches that of the pre-programmed target it instructs the guidance system to attack it. Eventual application of artificial intelligence is expected to provide future ASMs with considerable decision making capability, including allowing avoidance of decoys and providing for on-the-spot selection of the most valuable or most threatening target.

Recent events have shown that the British destroyer Sheffied during the Falkland Conflict in 1982 and the US frigate Stark in the Persian Gulf in 1987 were attacked by ASMs. .Even though these ships were equipped with anti-ASM weapons, these weapons could not be brought to respond in the time to defend against the attacking Exocet missiles. These two incidents illustrate that the defensive responses of the attacked ship must be fast and accurate to avoid serious casualties.

B. CHARACTERISTICS OF ANTI-SHIP MISSILS

Anti-ship missiles (ASMs) function by detecting the energy emitted or reflected by the target, analyzing the information, and by logic systems of varying degrees of complexity, determining the attack trajectory. They can be subdivided into the following categories :

1. **Radar Guidance Missile :**
    - Active and semi-active homing.
    - Using the energy reflected by a target illuminated by an emitter located inside the missile or externally.
2. **Infrared/TV Guidance Missile :**
    - Passive homing.
    - Using the actual energy radiated by the target (optical, eletro-optical,passive electromagnetic etc.).
3. **Anti-Radiation Missile :**
    - Directing the missiles on to the radar emissions of ships, in particular navigation and surveillance radars.
    - Probably will soon be able to attack fire control radars, despite the difficulties of homing and tracking.

Future development of anti-ship missiles includes :

- Increase in launching distance.
- Improvement in the discretion and mobility of launching installations.
- Improved co-ordination between sea-skimming and diving attacks.
- Reduction of radar cross section by reducing missile dimensions and improving their shape.
- Reduction of infrared signatures by using more discrete modes of propulsion (ramjets, special propellants) and by non-propelled final trajectories.
- Increase in speed, currently Mach 0.9; rapid attainment of Mach 3.0 must be predicted.
- Increase in missile maneuvering.
- Programming of evasive action into attack trajectories.
- Increased efficiency of warheads with impact and proximity fuzes.
- Use of sophisticated seekers with improved resistance to countermeasures.
- Improvement of missile's resistance to hard-kill systems.

With these new features, one can conclude that detection of ASMs will become more difficult, requiring more time and effort in air defense execution. In addition, the effectiveness of hard-kill systems will be reduced against small, robust and agile missiles. Finally, reaction time will be drastically reduced.

III. COUNTERMEASURE TACTICS AGAINST ANTI-SHIP WEAPONS

A. COUNTERING MISSILE ATTACK

There are three feasible approaches to defend against ASMs : (1) launching a preemptive strike against the source of the threat; (2) intercepting the missile in flight over long-to-medium-range; and (3) Close-in Weapon System, the CIWS.

Traditional means of countering an air attack is done through layered defense. Basically, this concept of defense involves several zones of engagement starting from the far reaches of the outer air battle down to the innermost air defense zone as Figure 3-1.

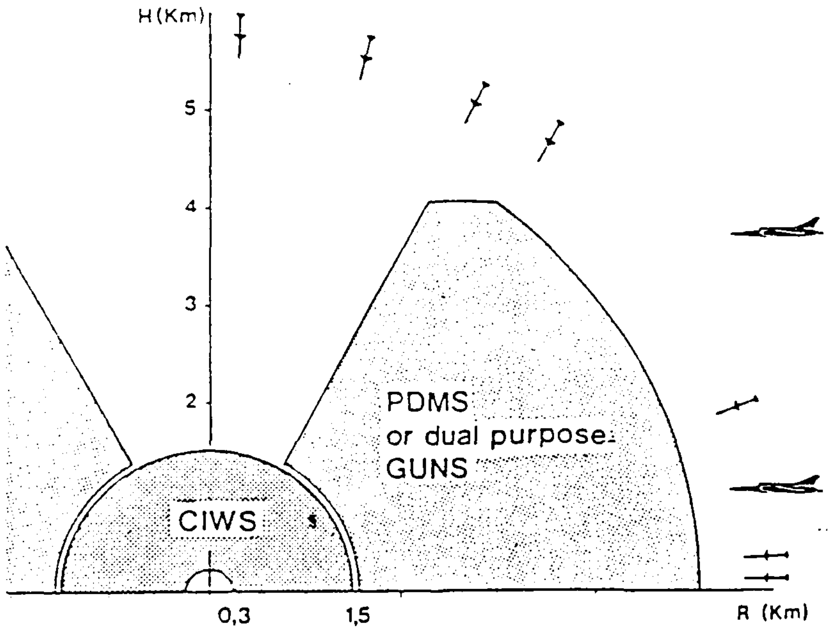


FIGURE 3-1 THE BASIC AIR DEFENSE ZONES

Each zone has a set of corresponding weapons assigned to it to reduce the chance of an anti-ship missile reaching its target. This means that attackers are successively employed in each zone by long-range, medium-range, and short-range (or point defense) weapons and by close-in weapon systems (CIWS). Ideally, it would be better to destroy an attacking platform before it could fire its weapons.

Multi-layered defense requires several distinct weapon systems with different capabilities and can be prohibitively expensive. Therefore, the degree of protection varies according to the size of a navy and the number of layers it can afford.

Although it is highly desirable to "kill" the platforms before missile firing, no guarantee can be made that such action could always be successfully executed. Failure to destroy the launching platform should result in the activation of either the "soft-kill" (using decoys such as chaff or flares and other electronic countermeasures) or "hard-kill" (anti-missile missiles or air defense guns) measures or both to confront the incoming threat. Figure 3-2 shows the basic defense tactics of a single ship.

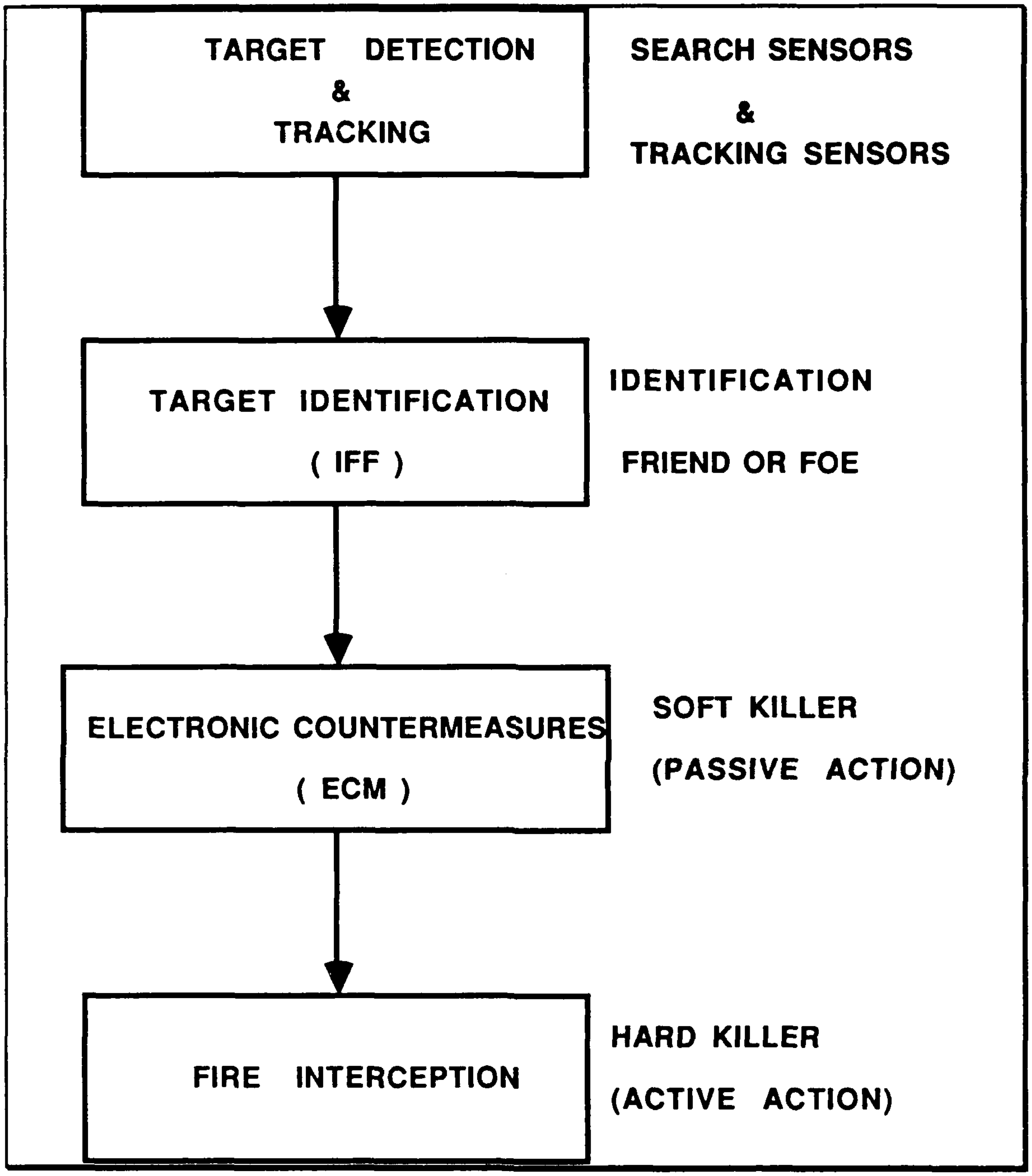


FIGURE 3-2 BASIC DEFENSE TACTICS OF A SINGLE SHIP

The high-accuracy and high-agility of modern anti-ship missiles, with relatively small radar cross-section, are rather difficult to detect. The ship

being attacked will have little time to react. Relying solely on human operators for target detection, acquisition, tracking, missile launch preparation, initiation of the launching sequence, and assessment of target destruction (so that another target would have to be engaged), will consumed too much precious time. One should bear in mind that even a fraction of a second should not be wasted considering that an attacking missile is only seconds away from impact. Time is therefore a very critical factor if one is to avoid the havoc.

To speed up the reaction time, time-consuming human decision making should be limited to critical decisions such as whether or not to attack. To achieve this, Combat Directional Systems are being developed which automate and integrate many shipboard systems.

B. BASIC DEFENSE TACTICS OF A SHIP

From Figure 3-2, a ship's defense against ASMs includes balancing capabilities of hard-kill and soft-kill, of active and passive measures and of point and area coverages with the mechanics and logic of the tactical interaction between defending and tracking weapons systems.

The attacking cycle depends first on detecting adversary. Detection will be made by either active or passive means. Active detection includes radar, acoustic and infrared as well as direct and indirect means such as tracking radar receives its own radar wave reflected from the target. Passive detection includes detecting the active radar, electron acoustic and other power sources such as Electrical Counter Measure (ECM) from the would-be target. Passive measures also include code-breaking and other intelligence related data leading to detection.

After initial detection is gained, specific location and identification are usually necessary before weapons can be launched with any degree of confidence of hitting their targets. Active detection and targeting sensors, in turn, are subject to passive detection by the defense, thereby providing alert and warning.

Once a targeting solution is obtained (with sufficient confidence or reason to shoot), weapons can be launched. The weapon must penetrate defense, detect, identify and lock-on to its target, and then hit. During this process, of course, an alerted and ready defense will be responding with a variety of hard- and soft-kill measures and point and area defenses.

C. SELECTION OF THE COUNTERING WEAPONS

A battleship is equipped with hard-kill weapons, such as missiles and guns, to defend itself by physically destroying the attackers. In addition, it will be fitted with soft-kill equipment, such as Electronic Warfare equipment which can be used in defense to confuse and deflect enemy hard-kill weapons. All these facilities operate based on information provided by sensors and on directions from the ship's combat center. Of course, they also require services such as electrical power and cooling water.

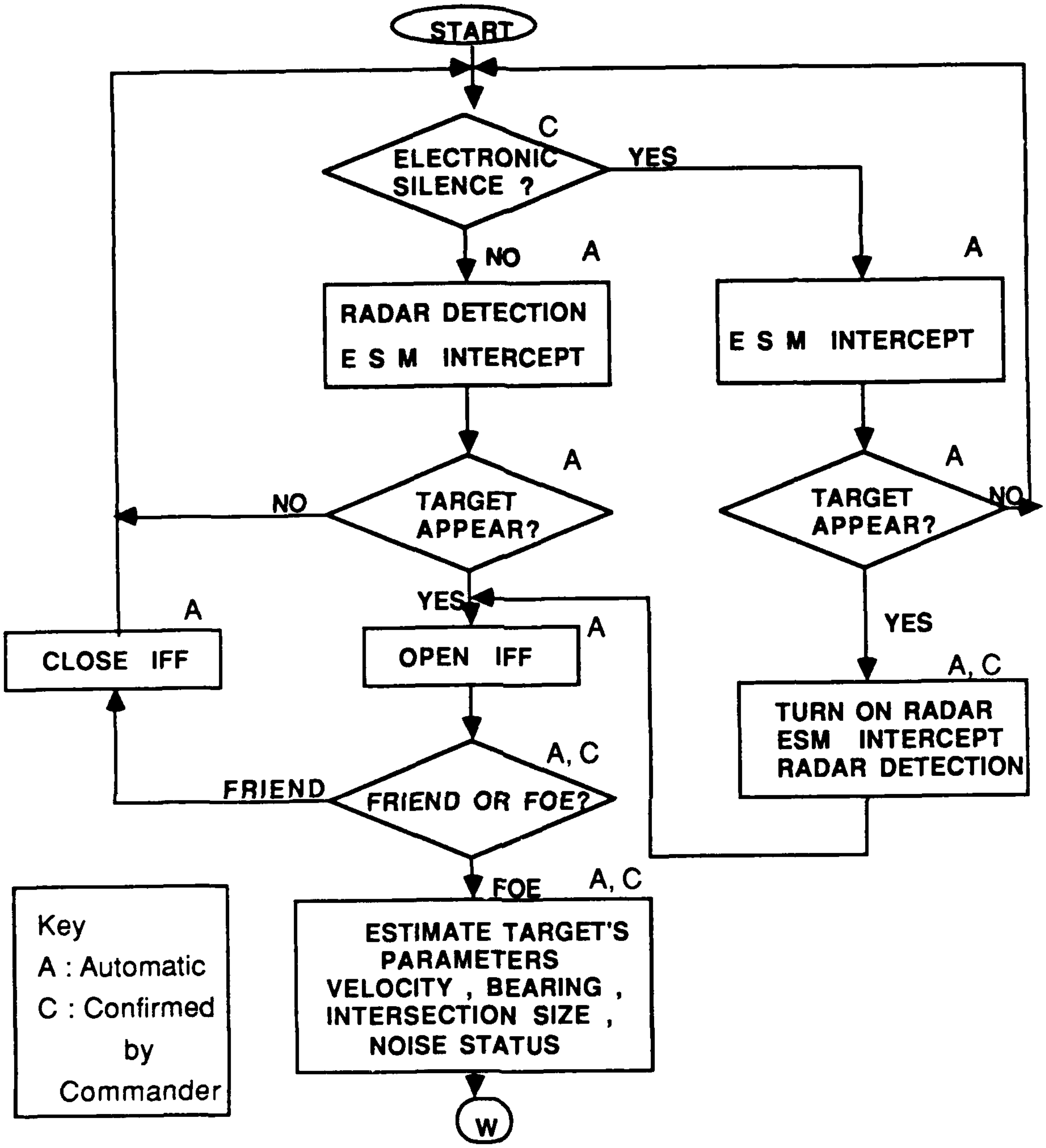
The most effective weapons against missiles or aircrafts are anti-missile missiles. Missiles which are launched from nearby enemy submarines or are at low altitude are only detected at short range. Battleships also need protection when such missiles are coming directly towards them. This protection is essential if the ships are operating outside any area air defense. However, even with the cover of area air defense, some missiles will succeed in penetraing the defenses (In this thesis, we only consider point defense problems, omitting area defense problems.). Point Defense Missile Systems (PDMS) (Figure 3-1) are

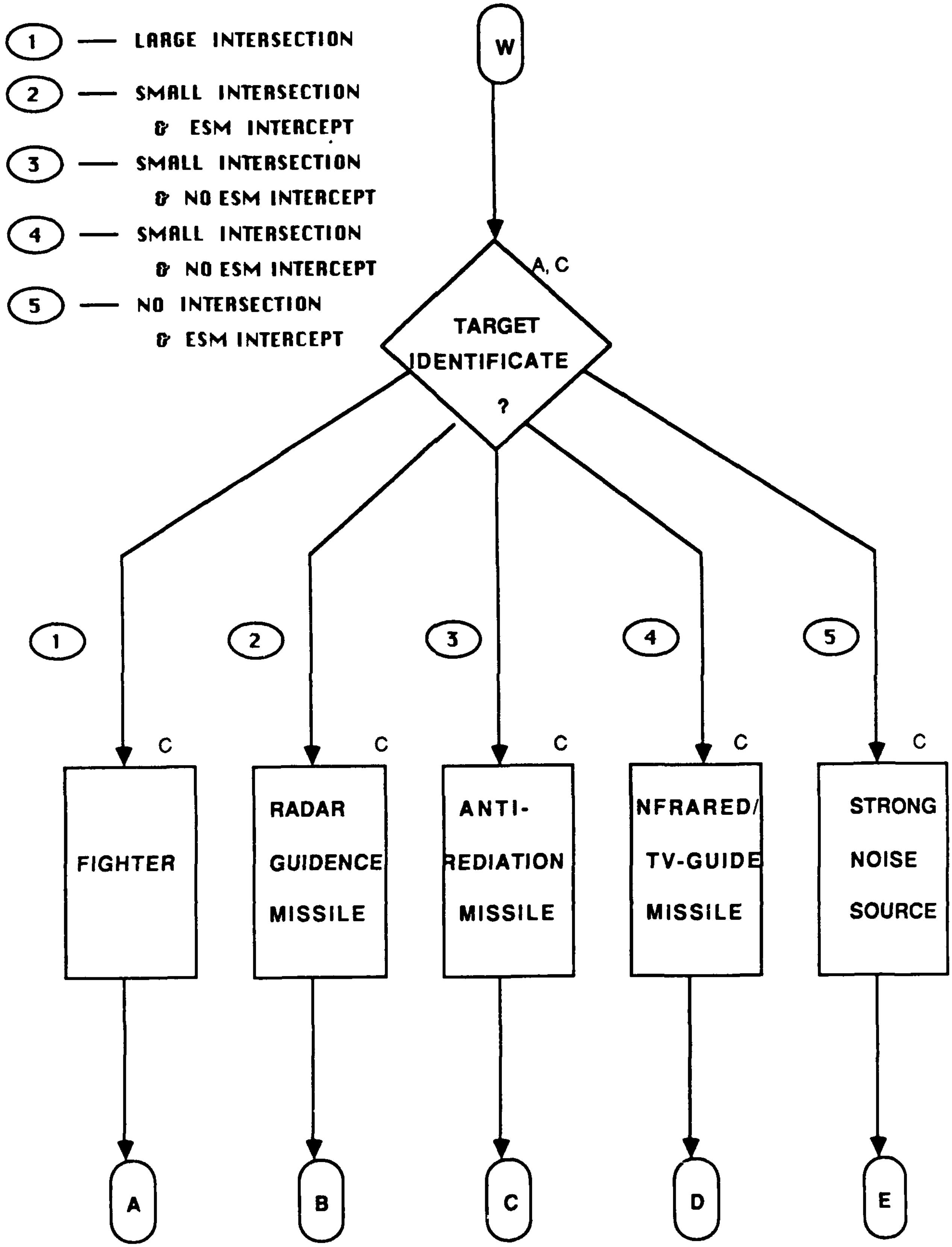
designed to counter this threat. The incoming missile is detected by a radar, and tracked by a Tracker radar. A point defense missile can be fired directly towards its target and travels up a reference beam transmitted by the Tracker towards the target. Mid-range guns can also be fired in time.

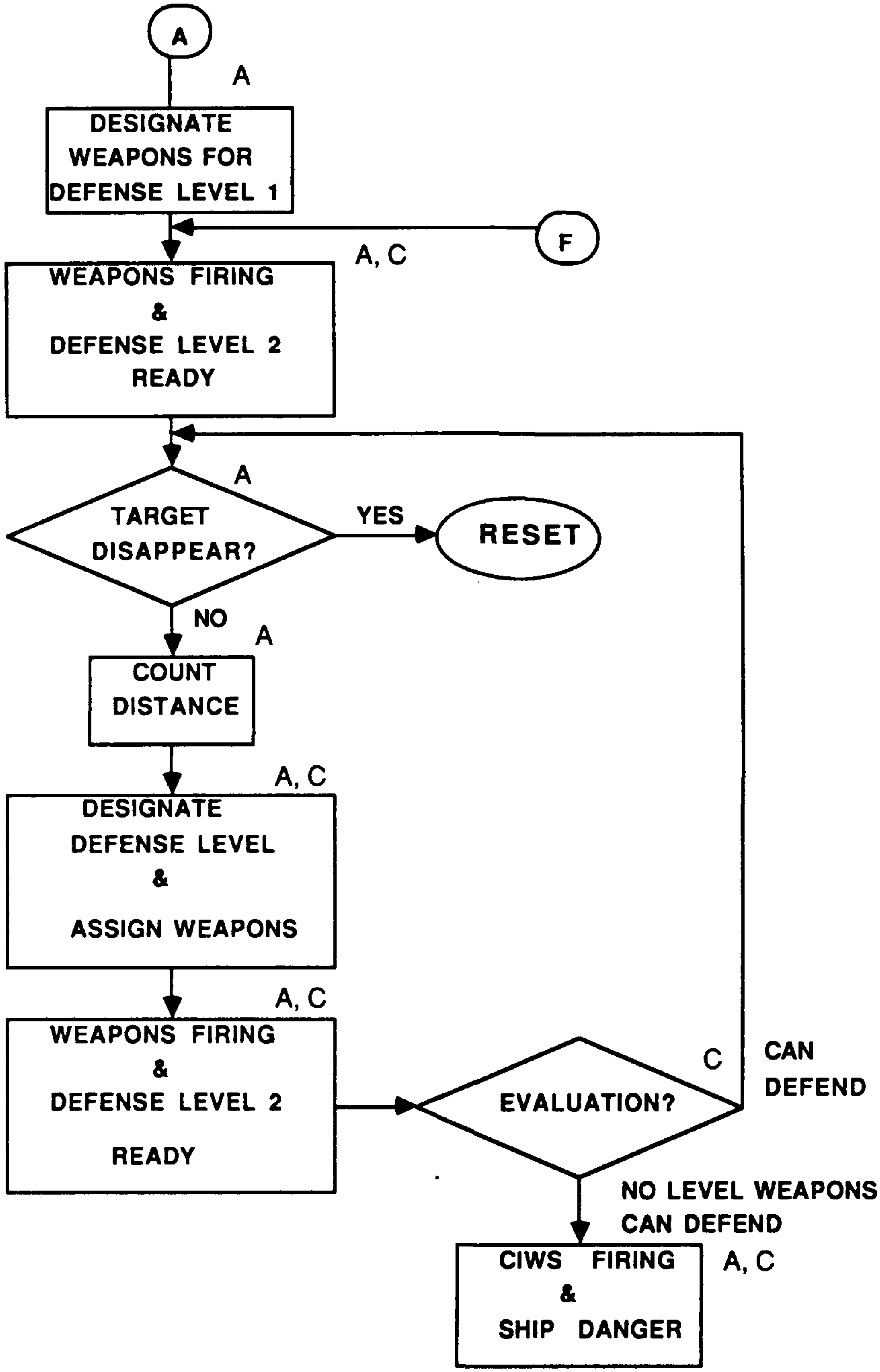
Missiles guns which successfully come within a short distance (2-3 kilometers) of the ship must be dealt with using the final "last-ditch" hard-kill weapon, the anti-missile guns of the Close-in Weapon System (CIWS)(Figure 3-1). These guns are small calibre radar-controlled guns, capable of firing short bursts of a large number of rounds. They are designed to explode the warhead of the incoming missile prematurely. Even if they achieve this, at such short ranges some treatments will probably reach the ship but these will cause far less damage than a warhead exploding within the ship.

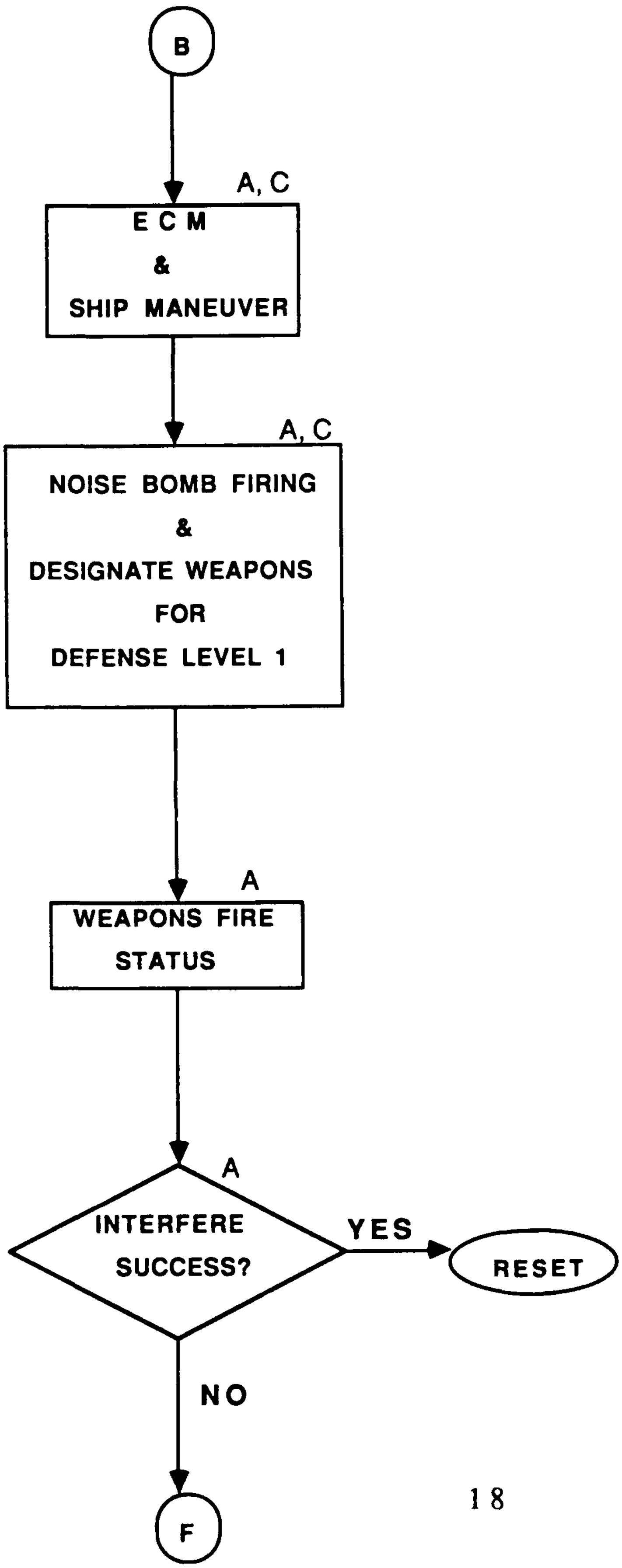
D. DEVELOPMENT OF THE OPERATIONAL PROCEDURE

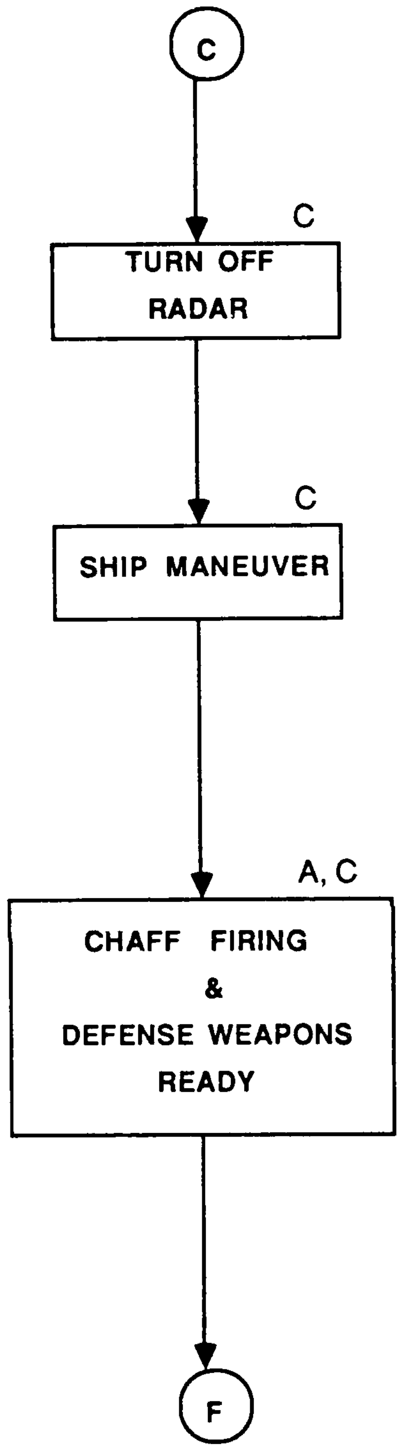
According to the above analysis of the characteristics of anti-ship weapons and the ship's countering tactics, we can design an air defense operational procedure. We use a flow chart to illustrate the operational procedures, as depicted below :

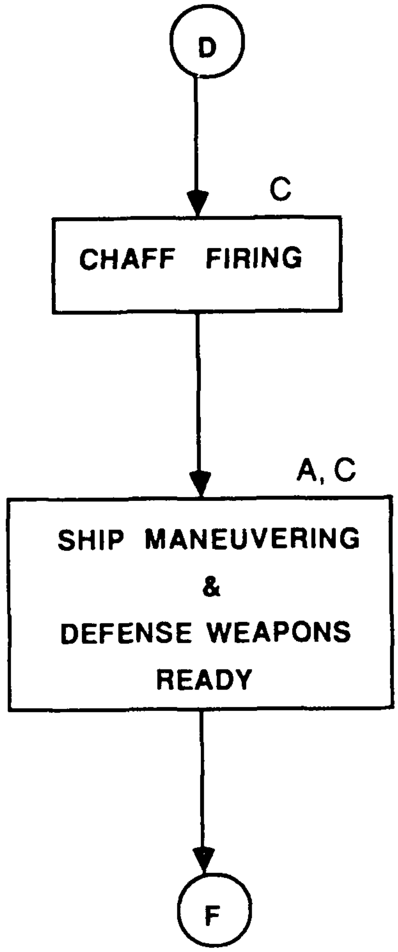

START
ELECTRONIC SILENCE ?
C
YES
NO
A
RADAR DETECTION
E S M INTERCEPT
A
E S M INTERCEPT
TARGET APPEAR?
A
NO
TARGET APPEAR?
A
NO
YES
CLOSE IFF
A
OPEN IFF
A
YES
A, C
TURN ON RADAR
ESM INTERCEPT
RADAR DETECTION
FRIEND
FRIEND OR FOE?
A, C
FOE
A, C
ESTIMATE TARGET'S PARAMETERS
VELOCITY , BEARING ,
INTERSECTION SIZE ,
NOISE STATUS
W
Key
A : Automatic
C : Confirmed by Commander

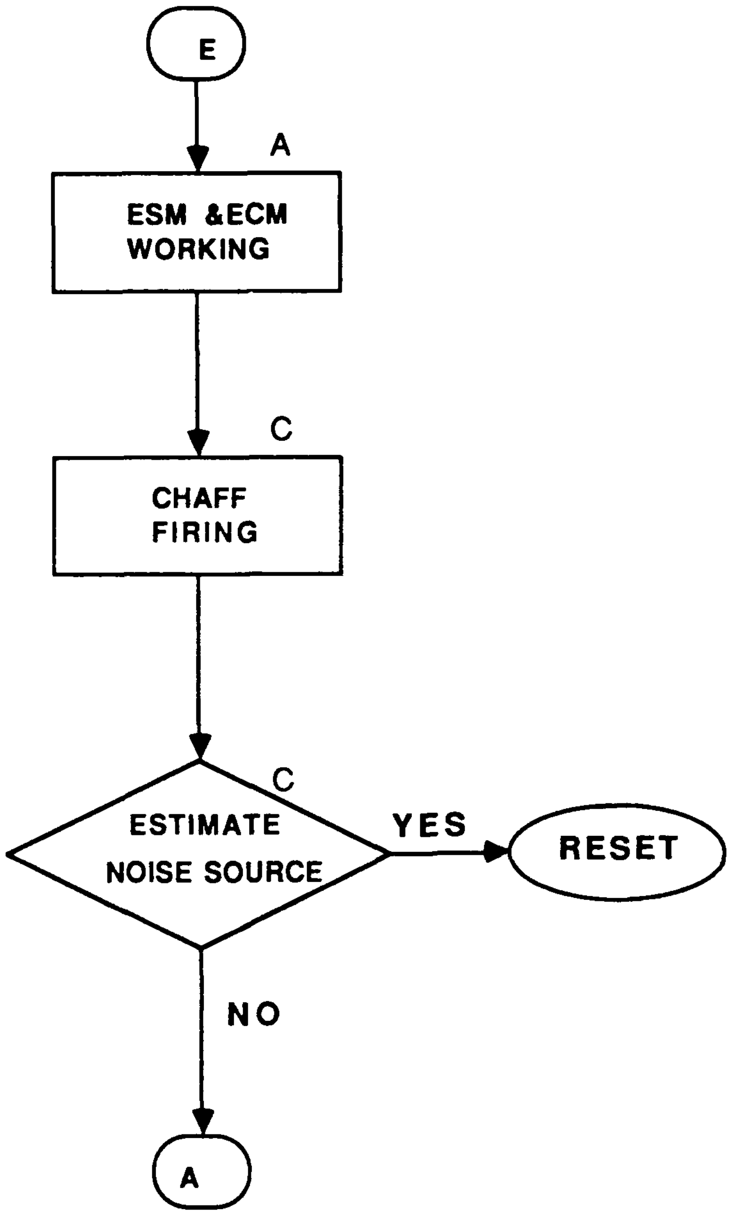

1 — LARGE INTERSECTION
2 — SMALL INTERSECTION & ESM INTERCEPT
3 — SMALL INTERSECTION & NO ESM INTERCEPT
4 — SMALL INTERSECTION & NO ESM INTERCEPT
5 — NO INTERSECTION & ESM INTERCEPT
W
A, C
TARGET IDENTIFICATE ?
1
2
3
4
5
C
FIGHTER
RADAR GUIDENCE MISSILE
ANTI-REDIATION MISSILE
NFRARED/ TV-GUIDE MISSILE
STRONG NOISE SOURCE
A
B
C
D
E


A
A
DESIGNATE WEAPONS FOR DEFENSE LEVEL 1
F
A, C
WEAPONS FIRING & DEFENSE LEVEL 2 READY
A
TARGET DISAPPEAR?
YES
RESET
NO
A
COUNT DISTANCE
A, C
DESIGNATE DEFENSE LEVEL & ASSIGN WEAPONS
A, C
WEAPONS FIRING & DEFENSE LEVEL 2 READY
EVALUATION?
C
CAN DEFEND
NO LEVEL WEAPONS CAN DEFEND
CIWS FIRING & SHIP DANGER
A, C


B
A, C
E C M
&
SHIP MANEUVER
A, C
NOISE BOMB FIRING
&
DESIGNATE WEAPONS
FOR
DEFENSE LEVEL 1
A
WEAPONS FIRE
STATUS
A
INTERFERE
SUCCESS?
YES
RESET
NO
F


C
C
TURN OFF RADAR
C
SHIP MANEUVER
A, C
CHAFF FIRING
&
DEFENSE WEAPONS
READY
F


D
C
CHAFF FIRING
A, C
SHIP MANEUVERING
&
DEFENSE WEAPONS
READY
F



In the air defense warfare, ship's active sensors (searching and tracking radars) and passive sensors (ESM) supply the early warning for possible intruders. The maximum defense range of the ship depends on the sensor's maximum detection range. Ideally, the ESM equipments will intercept the threat first.

When the sensor's operators discover a target on the screen, the commander must identify the target first. If the target is a friend, then the sensors should ignore the target and continue their operation. If, on the other hand, the target is unknown, the commander must determine if the target is hostile or not. If the unknown target is heading towards the ship, the commander must assume that the target is hostile and the ship must standby for fighting immediately. The following sequence of the operational procedures should be executed, until the target disappears.

- Analyze the target's parameters (such as velocity, bearing, intersection size and noise status, etc.) and identify if the target is a fighter, missile or just noise source.
- Use special ECM to decoy the target--decoys are real electronic targets, and by far are the most potent form of ECM in providing protection to ships by reducing the lethality of missile and causing them to miss their targets.
- Fire anti-air weapons, if ECM fails to distract the hostile target. This means that target are engaged in each zone by anti-air missiles, guns and close-in weapon systems (CIWS).

IV. DEFINING AN EXPERT SYSTEM STRUCTURE

A. FUNCTIONS OF AN EXPERT SYSTEM

To build an expert system one usually has to develop the following functions:

- Problem-solving functions capable of using domain-specific knowledge which may require dealing with uncertainty.
- User-interaction function, which includes explanation of the system's intensions and decisions during and after the problem-solving process.

An expert system is a computer program that behaves like an expert in some, usually narrow, domains of application. Typical applications include tasks such as medical diagnosis, locating mechanical failures, or interpreting measurement data. Expert systems are also called knowledge-based systems because they have to possess domain-specific knowledge necessary for solving problems. An expert system also has to be capable of explaining its reasoning and decisions to the user, as human experts do. Such an explanation feature is especially necessary in uncertain situations in order to enhance the user's confidence in the system's advice, or to enable the user to detect a possible flaw in the system's reasoning. Therefore, an expert system has to have a friendly user interface so that users can interact easily with the system.

An additional feature that is often required of an expert system is the ability to deal with uncertainty and incompleteness. Information about the problem to be solved can be incomplete or unreliable; relations in the problem domain can be approximate. For example, we may not be sure that some symptom is present in the patient, or that some measurement data is absolutely correct; some drag

may cause some problem, but usually does not. All this requires probabilities reasoning.

B. MAIN STRUCTURE OF AN EXPERT SYSTEM

It is convenient to divide the development of an expert system into three main modules, as illustrated in Figure 4-1:

- a knowledge base,
- an inference engine, and
- a user interface.

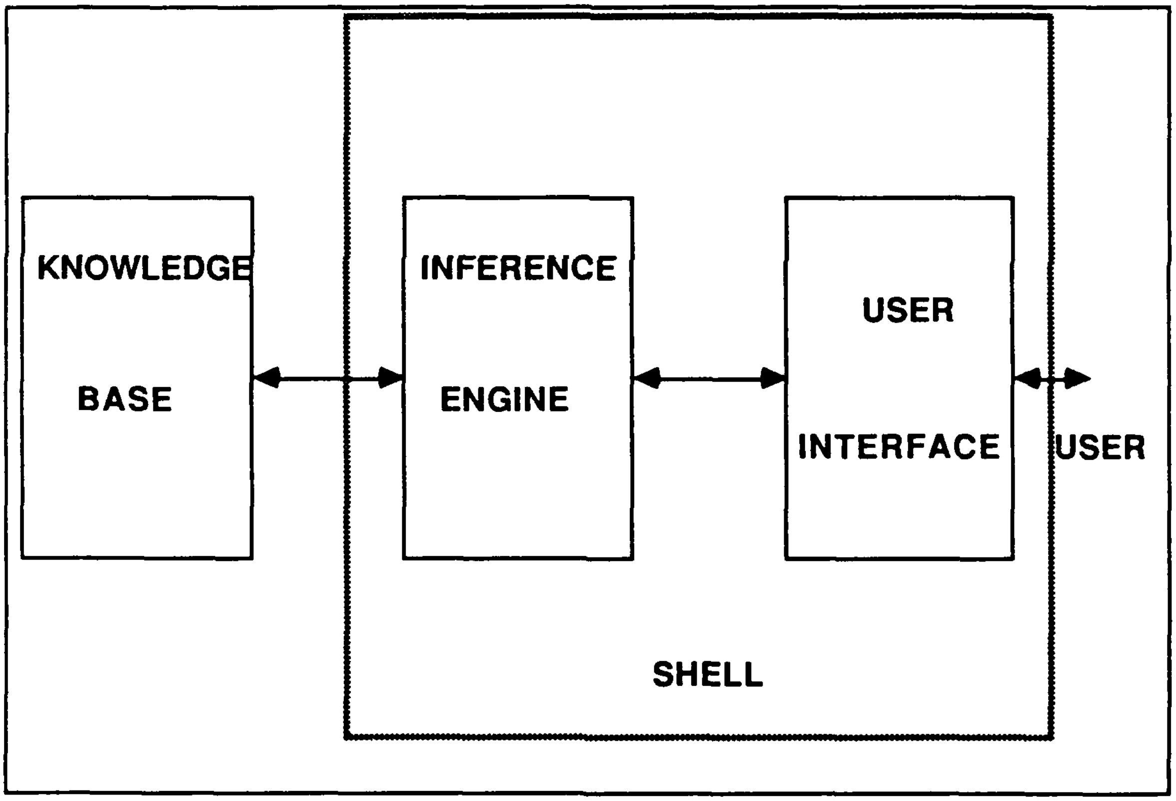


FIGURE 4-1 THE STRUCTURE OF EXPERT SYSTEM

A knowledge-base comprises the knowledge that is specific to the domain of application, including such things as simple facts about the domain, rules that describe relations or phenomena in the domain, and possibly also methods, heuristics and ideas for solving problems in this domain. An inference engine knows how to actively use the knowledge in the base. A user interface caters for smooth communication between the user and the system. It also provide the user with an insight into the problem-solving process carried out by the inference engine. It is convenient to view the inference engine and the interface as one module, usually called an expert system shell, or simply a shell for brevity.

C. WHO IS INVOLVED IN EXPERT SYSTEM CONSTRUCTION ?

The main players in the expert system game are the expert system, the domain expert, the knowledge engineer, the expert-system-building tool, and the user. Their basic roles and their relationship to each other are summarized in Figure 4-2.

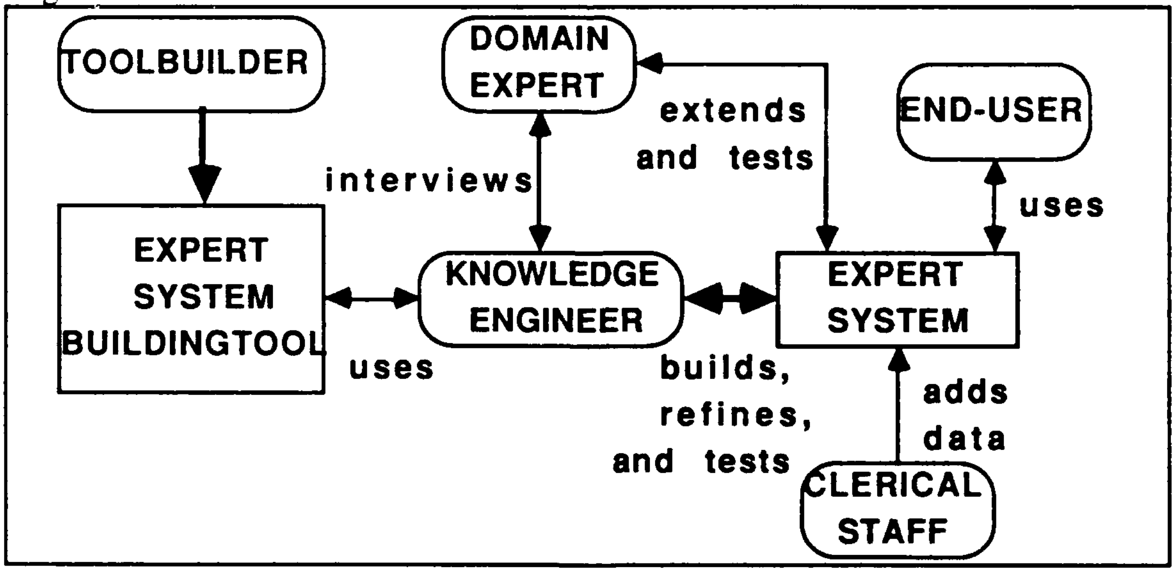


FIGURE 4-2 THE PLAYERS IN THE EXPERT SYSTEM GAME

The expert system can be regarded as a collection of computer software that solves problems in the domain of interest. It's called a system rather than just a program because it contains both a problem-solving component and a support component. This support environment helps the user interact with the main program and may include sophisticated debugging aids to help the expert-system builder test and evaluate the program's code, friendly editing facilities to help the experts modify knowledge and data in the expert system, and advanced graphic devices to help the user input and read information as the system is running.

The domain expert is an articulate, knowledgeable person with a reputation for producing good solutions to problems in a particular field. The expert uses heuristics and reasoning to search for a solution, and the expert system models these problem-solving strategies. Although an expert system usually models one or more experts, it may also contain expertise from other sources such as books and journal articles.

The knowledge engineer is a human, usually with a background in computer science and AI, who knows how to build expert systems. The knowledge engineer interviews the experts, organizes the knowledge, decides how it should be represented in the expert system, and may help programmers write the code.

An expert-system-building tool is the programming language and its associated support facilities used by the knowledge engineer or programmer to build expert systems. These tools differ from conventional programming languages in that they provide convenient ways to represent complex, high-level concepts.

The user is the human who uses the expert system once it is developed. The term user is a bit ambiguous. It normally refers to the end-user, the person for

whom the expert system was developed. However, in this thesis it will refer to anyone who uses the expert system. As Figure 4-2 suggests, the user may be a tool builder debugging the expert-system-building language, a knowledge engineer refining the existing knowledge in the system, a domain expert adding new knowledge to the system, an end-user relying on the system for advice, or a member of the clerical staff adding data to the system.

D. STAGES OF EXPERT SYSTEM BUILDING

A key to success in building an expert system is starting small and building incrementally to a significant functioning system. Empirical validation must be carried out at various stages of the refinement progress.

1. Initial Knowledge Base Design Stage:

This comprises three principal stages:

a. Problem Definition:

Which includes the specification of goal, constraints, resources, participants and their roles.

b. Conceptualization:

Which includes a detailed description of the problem, decomposing tasks into subproblems, elements of each subproblems (in terms of hypotheses, data, and intermediate reasoning concepts), and how these conceptualizations affect possible implementation.

c. Computer Representation of the problem:

Which includes specific choice of representations for the elements identified during the conceptualization phase. This is the first phase that requires computer implementation. Questions regarding information flow and articulation of the concepts and data will be raised more completely at this stage.

2. Prototype Development and Testing Stage:

Once the representation has been chosen, we can begin to design and implement a prototype system. The choice of subset is crucial: it must include a representative sample of the knowledge that is typical of the overall model, yet it must involve subtasks and reasoning that are sufficiently simple to test. Once the prototype produces acceptable results, it can be expanded to include more detailed variants of the problems it must solve. Then it will be tested with more complex cases that will be used as a standard test set for subsequent refinement of the knowledge base. Many adjustments of the primitive elements and their relationships are bound to come about as the result of this testing.

3. Refinement and Generalization of the Knowledge Base:

This stage can take a considerable amount of time if we expect to reach truly expert level performance.

E. A KNOWLEDGE-BASED SYSTEM FOR NAVAL AIR DEFENSE

We have discussed what the expert system is, how it could be implemented, and the importance of expert systems in naval command and control affairs. This chapter discusses how the expert system works in the ship's air defense combat system.

The proliferation of threats to the safety of modern battleships since World War II has tended to outstrip the ability of ship's combat systems to defend them, leaving them vulnerable to a determined, co-ordinated attack. Naval warfare has increasingly become a long range affair. From underwater, air curise missiles may be launched, and above the water missiles may be launched to home in on infrared or electro-magnetic emissions. Some missiles are also able to use their own radar in the final phase of the attack, approaching from any direction and

from sea level zenith. The key to effectively handling the modern threat is to manage the relevant information and produce an accurate, comprehensive picture of the area surrounding a surface ship. The size of the area covered will obviously depend upon the threat.

The modern battleship has an impressive array of sensing equipments: (1) Radars: there are two or three tracking radars optimized for short range high definition work, and one or more searching radars for long range air warning. (2) Sonars: passive sonars detect passively that have good ability to detecting submarines at very long range such as towed arrays, and active sonars with complex signal processing effective at medium and short range and for weapon control. (3) Electronic warfare equipments: ESM equipments intercept enemy's electro-magnetic emissions. In addition, there are electro-optic sensors, reports received by radio, and background intelligence information.

In order to compile the picture it is necessary for the shipboard systems to detect, locate, track and, if possible, classify all objects, which might possibly contribute to the tactical situation. The tactical data link will be used to add objects seen from other units of the force. All the information then has to be interpreted, collated and fused to form one comprehensive force tactical picture.

Commander cognitive overload, as it is known, is widely recognized as a key problem. The increasing volume of incoming information must, nevertheless, be assimilated, interpreted and assessed by the Officer of Tactical Command (OTC). It is, therefore, desirable that the OTC receives automated decision aids. These aids will not only support the gathering and classification of available information in a timely manner, but also provide, to the OTC, an effective

presentation of the resulting tactical picture with necessary explanations, assessments and recommendations for action.

According to the above analysis, we have designed a structure of ship's air defense knowledge-base system, as show in Figure 4-3 :

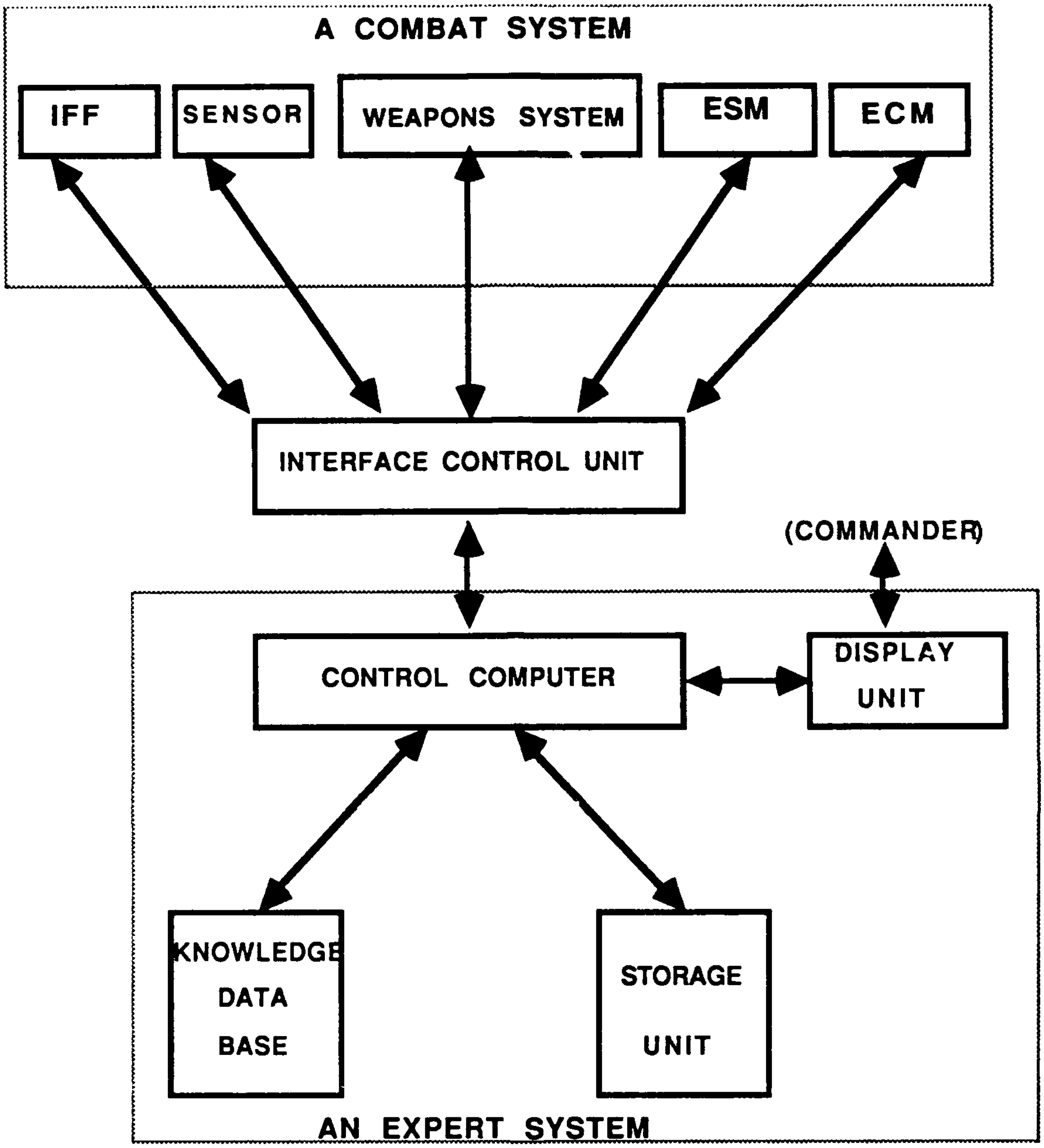


FIGURE 4-3 THE STRUCTURE OF SHIP'S AIR DEFENSE KNOWLEDGE-BASE SYSTEM

This system consists of the following units:

1. **Interface Control Unit :**

The primary of role of the interface control unit is the exchange of data between the ship combat system and the air defense expert system. The interface control unit accepts data from commander via expert system and sends orders to the combat system. Feedback from sensors/weapons are returned to the expert system for processing and display to the commander.

2. **Display Unit (input/output unit) :**

This module will provide a means of control by the commander as well as output for both the knowledge based system and the tactical situation. The operator will be able to interrogate the system to determine the reasoning behind an assessment or recommendation and, if necessary, to monitor or provide decision-making inputs.

3. **Control Computer :**

This is the center of the whole structure. The responsibilities of the control computer is to supervise the status of all weapons and sensor units, and to supply decision-making supports that take into consideration different situations and operational procedure rules.

4. **Knowledge Data Base :**

This module is the source of "knowledge" which stores the operational procedure rules for control computer inferencing, allocating, and consulting.

V THE DESIGN OF THE SHIPBOARD AIR DEFENSE SYSTEM

A. DESIGNING RULES IN THE KNOWLEDGE BASE

In Artificial Intelligence, a representation of knowledge is a combination of data structures and interpretive procedures that, if used in the right way in a program, will lead to "knowledgeable" behavior.

Our Shipboard Air Defense System is a "rule-based" system which possesses a large amount of knowledge in naval air defense and is able to develop a high level support in tactical decision-making.

All the preplanned responses in our system are contained in a set of inferential knowledge represented as production rules. The basic idea is that the knowledge base consists of rules called productions, in the form of condition-action pairs :

IF this-condition-occurs,

[THEN do-this-action]

[ELSE do-other-action]

The use of the knowledge in our system involves retrieving rules relevant to the problem at hand from the knowledge base and solving the problem. The rules in the knowledge base are designed according to the defensive operational procedures discussed in Chapter III. A simple example is listed below :

****

RULE NUMBER : 1

IF : Need to Maintain electronic silence

THEN : Monitor ESM

ELSE : Open radar

****

RULE NUMBER : 2

IF : Target appears on ESM

THEN : Open radar

****

RULE NUMBER : 3

IF : Target appears on radar

THEN : Identify Friend or Foe

ELSE : Reset System

****

****

RULE NUMBER : 4

IF : Target not a friend

THEN : Check if Target is heading towards ship

ELSE : Reset System

****

RULE NUMBER : 5

IF : Target is heading toward ship

THEN : Target status is hostile - verify

ELSE : Reset System

****

RULE NUMBER : 6

IF : Target shows - large intersection on radar

THEN : Target is fighter

ELSE : Target is missile

****

****

RULE NUMBER : 7

IF : Target is missile and appears on ESM

THEN : Target is radar-guided missile

ELSE : Target is anti-radiation or infrared/tv-guide missile

****

RULE NUMBER : 8

IF : Target is fighter

THEN : Designate weapons for level 1 defense

****

RULE NUMBER : 9

IF : Target is radar-guided missile

THEN : Turn on ECM; turn ship towards target; fire CHAFF

****

****

RULE NUMBER : 10

IF : Target is anti-radiation missile

THEN : Turn off radar; turn ship towards target; fire CHAFF

****

RULE NUMBER : 11

IF : Target is infrared/tv-guide missile

THEN : Turn ship towards target; fire CHAFF

****

RULE NUMBER : 12

IF : ECM Interference is successful

THEN : Reset system

ELSE : designate weapons for level 1 defense

****

****

RULE NUMBER : 13

IF : Designate weapons for level 1 defense

THEN : Fire defensive weapons

****

RULE NUMBER : 14

IF : Fire defensive weapons

THEN : Activate Level 2 defense

****

RULE NUMBER : 15

IF : Target has been destroyed or disappeared

THEN : Reset system

ELSE : Evaluate situation

****

****

RULE NUMBER : 16

IF : Can still defend against target

THEN : Fire defensive weapons

ELSE : CIWS firing

****

RULE NUMBER : 17

IF : CIWS firing

THEN : Ship in danger - start praying

****

B. SOFTWARE IMPLEMENTATION

Given the above analysis on anti-ship weapons, counter attack measures, and decision procedures in tactical situations, we have designed and implemented a computer program that simulates the behavior of an intelligent air defense system.

The program was written in C-Prolog and consists of two major components: the inference engine and the rule base.

1. The Inference Engine

The inference engine is basically a forward chaining interpreter. It works from known facts and infers decisions based on the rules defining the problem solving strategies. Its structure is as follows:

```
eval ( Action ) : -
        rule ( Action ),
        write ( Action ).
eval ( Condition ) : -
        rule ( Condition , Action ),
        eval (Condition ).
eval ( Condition ) : -
        rule ( Condition , True_action , False_action ),
    query ( Condition , Reply ),
    ( affirmative ( Reply ) ->
            eval ( True_action );
            eval ( False_action )).
```

Once invoked, the interpreter fires the rule that has its condition matched against the facts. The actions associated with the rule is then performed and a new rule is fired based on this action.

The first clause above deals with the situation when a conclusion is reached. The interpreter simply perform the action defined in the rule. The second clause handles the unconditional rule where an action is always executed when the condition specified in the rule is confirmed. The third clause is for conditional rules when the condition has to be verified by some external oracle. In the current program, the oracle is played by the system user. However, in a

battleship environment, this oracle can be a sensor or data-link that provides the necessary information.

2. The Rule Base

The rule base consists of rules of the form

IF this-condition-occurs,

[THEN do-this-action]

[ELSE do-other-action]

where [...] means the component is optional.

For example, the top level rules is:

```
rule ( 'Maintain electronic silence?',
       'ESM intercept - target appears?',
       'Open radar - target appears?' ).
```

which means if the ship maintains electronic silence, then ESM is in open condition and is passively checking whether a target appears on ESM; on the other hand, if the ship does not maintain electronic silence, then it will open the radar and check whether a target appears on radar.

There are currently 17 rules in the rule base, representing air defense knowledge in tactical situations. The rules developed for this thesis are implemented in Prolog as follows:

```
rule( 'Maintain electronic silence?' ,
        'ESM intercept - target appears?',
        'Open radar - target appears?' ).

rule( 'ESM intercept - target appears?' ,
        'Target on ESM' ,
        'Maintain electronic silence?' ).

rule( 'Target on ESM' ,
        'Open radar - target appears?' ).

rule( 'Open radar - target appears?' ,
        'Target on radar' ,
        'Maintain electronic silence?' ).

rule( 'Target on radar' ,
        'IFF - Target a foe?' ).

rule( 'IFF - Target a foe?' ,
        'Target heading toward ship?' ,
        'Reset system' ).

rule( 'Target heading toward ship?' ,
        'Target hostile - large intersection on radar?' ,
        'Maintain electronic silence?' ).

rule( 'Target hostile - large intersection on radar?' ,
        'Target is fighter' ,
        'Target is missile - appearing on esm?' ).

rule( 'Target is missile - appearing on esm?' ,
        'Target is radar-guided missile' ,
        'Target is anti-radiation missile?' ).

rule( 'Target is anti-radiation missile?' ,
        'Target is anti-radiation missile' ,
        'Target is infrared/tv-guide missile' ).

rule( 'Target is fighter' ,
        'Designate weapons for level 1 defense' ).

rule( 'Target is radar-guided missile' ,
        'Turn on ECM; turn ship towards target; fire CHAFF ' ).

rule( 'Turn on ECM; turn ship towards target; fire CHAFF ' ,
        'Interference successful?' ).
```

```
rule( 'Target is anti-radiation missile' ,
        'Turn off radar; turn ship towards target; fire CHAFF ').

rule( 'Turn off radar; turn ship towards target; fire CHAFF ' ,
        'Interference successful?' ).

rule( 'Target is infrared/tv-guide missile' ,
        'Turn ship towards target; fire CHAFF' ).

rule( 'Turn ship towards target; fire CHAFF' ,
        'Interference successful?' ).

rule( 'Interference successful?' ,
        'Reset system' ,
        'Designate weapons for level 1 defense' ).

rule( 'Reset system' ,
        'Maintain electronic silence?' ).


rule( 'Designate weapons for level 1 defense' ,
        'Fire defensive weapons').

rule( 'Fire defensive weapons' ,
        'Level 2 defense ready' ).

rule( 'Level 2 defense ready' ,
        'Target destroyed or disappeared?' ).

rule( 'Target destroyed or disappeared?' ,
        'Reset system' ,
        'Can still defend against target?').

rule( 'Can still defend against target?' ,
        'Fire defensive weapons' ,
        'CIWS firing' ).

rule( 'CIWS firing' ,
        'Ship in danger - start praying' ).

rule( 'Ship in danger - start praying' ).
```

C. Simulation Results

A simple way to evaluate a system's performance is to assess how closely the system's performance satisfies the original goal. In this section, we present some test runs on various tactical situations.

- Case 1: Anti-radiation missile attack; Interference succeeds

Maintain electronic silence?

/ : n. ---Commander---

Open radar - target appear?

/ : y. ---Auto---

Targat on radar ...

IFF - Target a foe?

/ : y. ---Auto with confirm by Commander---

Target heading toward ship?

/ : y. ---Auto---

Taregt hostile - large intersection on radar?

/ : n. ---size Auto, conform hostile by Commander---

Target is missile - larget intersection on radar?

/ : n. ---Auto---

Target is anti-radiation missile?

y. ---confirm by Commander---

Target is anti-radiation missile ...

Turn off radar; turn ship towards target; fire CHAFF

Interference successful?

I : y. ---Auto---

Reset system ...

In this scenario, the ship operates with radars on, since it is not required to maintain electronic silence. When a target appears on radars, is a foe, is heading towards the ship, the system determines that it is hostile. The target also appears small and is not visible on ESM. Therefore, it is classified as an anti-radiation missile, and the system recommends actions such as turning off radars, turning ship towards target, and firing CHAFF. When the interference succeeds, the system is reset.

- Case 2: Radar guided missile attack; Countermeasure fails

Maintain electronic silence?

I : y. ---Commander---

ESM intercept - target appear?

I : y. ---Auto---

Target on ESM ...

Open radar - target appears?

I : y. ---Auto---

Target on radar ...

IFF - Target a foe?

I : y. ---Auto with confirm by Commander---

Target heading toward ship?

I : y. ---Auto---

Target hostile - large intersection on radar?

| : n. ---size Auto, confirm by Commander---

Target is missile - appearing on esm?

| : y. ---Auto---

Target is radar-guided missile ...

Turn on ECM; turn ship towards target; fire CHAFF

---confirm by Commander---

Interference successful?

| : n. ---Auto---

Designate weapons for level 1 defense ...

---confirm by Commander---

Fire defensive weapon ...

---confirm by Commander---

Level 2 defense ready ...

---confirm by Commander---

Target destroyed or disappeared?

| : n. ---Auto---

Can still defend against target?

| : y. ---Auto---

Fire defenive weapons ...

---confirm by Commander---

Level 2 defense ready ...

---confirm by Commander---

Target destroyed or disappeared?

/ : n. ---Auto---

Can still defend against target?

/ : n. ---Auto---

CIWS firing ...

Ship in danger - start praying ...

This scenario depicts the situation in which the ship's ESM intercepts a threatening target, opens radars and IFF equipments to identify the target, fusing all information and classifies the target as a radar guided missile. After ECM, long- and medium-range defensive weapons fails to destroy the missile, the ship is in extremly adverse condition and has to rely on CIWS firing for its survival.

- Case 3: Target is friend

Maintain electronic silence?

/ : y. ---Commander---

ESM intercept - target appear?

/ : y. ---Auto---

Target on ESM ...

Open radar - target appears?

/ : y. ---Auto---

Target on radar ...

IFF - Target a foe?

/ : n. ---Auto with confirm by Commander---

Reset system ...

In electronic silence condition, the ship's ESM intercepts a target bearing. The ship opens radars and IFF equipments to identify the target and confirmed the target is friend.

VI. CONCLUSION

A. SUMMARY

This thesis examines the practicality of using expert system approach in designing an intelligent air defense system to assist the Officer in Tactical Command (OTC) to make efficient and accurate decisions in critical situations in the battlefield. We outlined the problems and justified the need to automate the air defense decision process in Chapter I. In Chapter II we traced the development and analyzed the most effective anti-ship weapons including radar guidance, anti-radiation, and infrared/tv-guidance missiles. We then discussed the countermeasure tactics against anti-ship weapons in Chapter III. In Chapter IV we explained the basic concepts in the structure, design, and construction of expert systems. In Chapter V we presented a model based on discussions in earlier chapters, in the form of a rule-based system. The software implementation and simulation results were also detailed in the chapter.

B. FUTURE WORK

We have shown that the tactical knowledge, reasoning, and decisions in combat situations can be modelled adequately using production rules and expert system technology. However, to develop an automatic system operating in real-time for air defense will require the incorporation of a lot more resources including:

- multiple tracking sensors
- multiple weapons interfaces
- multiple tactical data link systems
- electronic warfare

It will be ideal if all the available units can be integrated together to form a complete combat system. Although this represents a long-term goal, we believe some of the problems can be resolved using today's technology. Example followups to this work include:

- How the expert system can automatically be combined with the ship's air defense system ?
- How to make a man-machine interface between the expert system and the Commander ?
- How to choose a expert system building tool for the intelligent air defense expert system of ship ?

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